scope configuration; however, it may be convenient in some applications to exchange the source 20 and detector 32 locations. Similarly, the PSM configuration 128 shown in FIG. 5 is preferred because is easier to manufacture to tighter alignment tolerances than the design that results by exchanging the source and detector. Again, in some situations, it may be advantageous to exchange source 20 and detector 32.

[0044] The fiber source 20 is shown offset a significant distance from the beam splitter cube 30a so that the camera 32 is also a significant distance from the beam splitter, thereby providing space for a moveable lens 62. The moveable lens 62 is left out of the light path when a point image is desired. Insertion of the moveable lens 62 in the path spreads the point of light out on the detector 32 so that interference of the light from the reference 30b and sample 24 may be observed with a sufficiently coherent source 20. The interference pattern present on detector 32 is preferably formed in conjunction with an image of sample 24; however, even if the image of sample 24 is poorly focused, it is possible to identify a null position of the fringe pattern to even higher precision than the best focus and alignment of the point image. It is also possible to design the system 128 so that the moveable lens 62 is in the optical path for point image and out of the path for the interference image. Or the system 128 may be made even more compact by leaving out the space for a moveable lens 62 and moving the point source 20 and camera 32 closer to beam splitter 30a.

[0045] An auxiliary lens mount 64 is included so that relay lenses (not shown) may be attached to change the working distance, numerical aperture, or both of the system 128. For example, a lens system 65 may be secured to the auxiliary lens mount 64, wherein the lens system includes a collimating lens 252 and an objective lens 226. The objective lens 226 with a longer working distance might be necessary to locate the center-of-curvature of a large convex surface or a larger numerical aperture might be used in locating the center of curvature of a fast lens; see FIG. 7a, which shows a relayed focal point 25'.

[0046] A collimated output beam may be obtained by leaving objective lens 226 out of the system or by the addition of an auxiliary lens having a collimated output 80, as shown in FIG. 7b, which depicts lens system 65' secured to the auxiliary lens mount 64. The collimated output 80 of a PSM is useful for measuring angles between planar sur-

faces or for the adjustment, in angle, of one planar surface relative to another by measuring the angle between specular reflections from planar surfaces .

[0047] An optional phase shifting module 66 is shown so that the distance between the focus point of objective lens 126 to either a surface 24 or the center of curvature of a surface 24 can be measured by implementing phase shifting methods, as is well known in the art. An image capture, computing means, software, and human or machine interface is required. The phase shifter, or optical path length modulator, 66 is shown schematically in FIG. 6 and in phantom in FIG. 5 between the beam splitter cube 30a and the sample 24. The principal of operation is to move a prism 68a orthogonal to the beam 69, as indicated by double-headed arrow A; as a result, the optical path length changes, since the index of refraction of the prism 68a and air are different. The changing optical path length results in phase shifting or modulation of the interference pattern seen on the detector 32 in interference mode. Mounting bracket 70 provides an interface to attach phase shifter 66 to PSM 128. Mounting post 72 is used to hold fixed prism 68b. Piezo-electric translator 74 is attached to mounting bracket 70 and functions as a mounting post for moving prism 68a. The length of the piezo-electric translator is a function of an applied voltage. Other similar methods of phase shifting will be obvious to those familiar with the art. If the PSM 128 does not allow for a phase shifting module 66, it can be made even more compact.

[0048] A collimating lens 52 may optionally be placed between the spherical reference surface 30b and the phase shifter 66.

[0049] The prisms 68a, 68b in the phase shifting module 66 may be oriented such that the optical axis of the output lens is minimally displaced from the optical axis of the reference surface 30b. This has the benefit of allowing a common mechanical axis to be used in fabricating the PSM components. Minimizing the spacing between the prisms 68a, 68b minimizes the amount by which the optical axes are displaced. However, this orientation results in a partial reflection from one or more surfaces of the prisms 68a, 68b, creating a point image on the detector 32. Anti-reflection coatings on the prisms 68a, 68b can be used to reduce or eliminate this problem. As an alternative design choice, the prisms 68a, 68b can be rotated so that any light reflected from the

prisms does not return to the detector 32; however, this will result in a displacement of the optical axes that requires more complicated mechanical fabrication.

[0050] It is possible to replace the plano-convex lens 30b in FIG. 5 with a concave spherical mirror (not shown) that is separated by a short distance from the surface of the beam splitter 30a. The spherical mirror will act as a reference surface 30b as before. The benefit of this substitution is that phase shifting can be accomplished by an axial translation of the mirror. The mirror could be mounted on a flexure to give axial or approximately axial motion with the motive force from a piezo-electric transducer. The phase-shifter 66 using prisms 68a, 68b is preferred because the output lens axis is closer to the housing making the PSM 128 more generally useful.

[0051] An electrical connector 86 is used to supply power to the detector, or camera, 32 and receive a video signal therefrom via connection 88 and to supply a voltage to the phase shifter 66 via connection 90.

[0052] A mounting adapter or stud 76 is included to make attachment of the PSM 128 to a coordinate measuring machine or other measuring apparatus or device convenient.

[0053] In both embodiments shown for the PSM 28, 128, the point source 20 of optical radiation is located at the apparent center of curvature of the spherical reference surface 30b.

<u>Applications</u>

[0054] The problem that motivated the present application was the alignment of a complicated optical system. The PSM 28, 128 provides a non-contact means of locating the defining feature of an optical surface – its center of curvature. Successful, practical experience was obtained by attaching a prototype PSM (FIGS. 3A-3B) based upon the Shack cube to a mill and using the mill bed to translate the optical system. Tooling balls were used to relate mechanical datums (e.g., hole locations, desired optical axis height) to optical datums – the centers of curvature of a series of lenses and mirrors – thereby greatly simplifying the alignment process by providing real time, visual feedback and maximizing the performance of the optical system. Tooling balls are com-